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Detailed Evaluation of Renewable Energy Power System Operation: A Summary of the European Union Hybrid Power System Component Benchmarking Project

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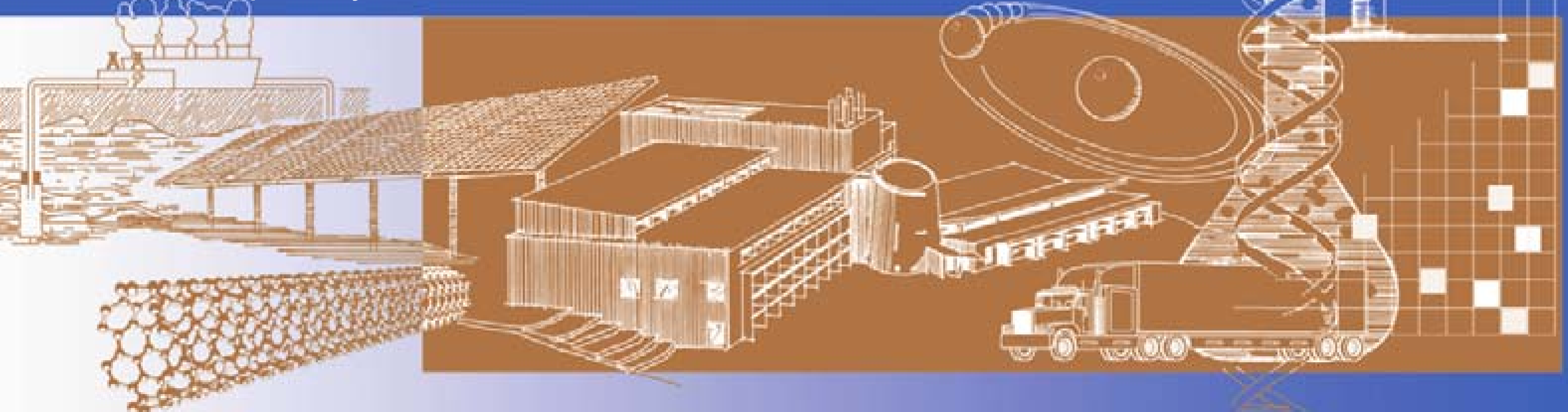

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1. Abstract

Hybrid renewable energy systems (RES's) are unique among energy supply systems because their performance and design depends entirely on the location and climatic conditions. A system optimized for an application in one location may be inadequate in another location, even if the application and user requirements are identical. Additionally, it is quite difficult to choose between different power system components (batteries, for example) because performance and life change dramatically based on the use profile that the component will experience. Currently, initial cost and basic performance are the only measures available to select among many similar components, although the true impact on system operation can be pronounced.

This paper describes the results of the European Union (EU) Benchmarking Project, a 3-year, multi-agency research project to improve the design of renewable-based hybrid power systems based on the analysis of existing systems and the benchmarking of specific system components, most critically batteries. Based on the analysis of hundreds of power systems, efforts were made to classify different categories of similar use and then determine component-specific recommendations that will allow more consistent and longer product life. Based on the classification of different use types, assessments of critical ware factors could be conducted and recommendations of appropriate component selection undertaken. The project results make it possible to match most systems to a use category, thus allowing recommendations to improve project life.

This paper describes the benchmarking methodology and describes the tools produced by the benchmarking team to improve the design of hybrid power systems.

2. Introduction

A battery can only be recommended as the best battery for a specific RES if it fulfils all performance requirements of the user to the highest degree and in a cost-efficient manner.

RES's are site specific. Without knowledge of the renewable energy resources, it is impossible to optimally plan the system, size its components, plan the operating regime, and select the most suitable components. In addition, no applications are identical, and even small variations may lead to differences in the energy throughput of the system and some critical operating conditions or their components. While making general recommendations for RES's and batteries is straightforward, making specific recommendations is impossible without a detailed analysis of the location and the application, including a sensitivity analysis concerning the various assumptions and their likely variations over time. For cost reasons, a detailed analysis can only be made for a large RES or an RES with special requirements. Most of the standard RES's for remote locations (e.g., farmhouses, remote villages, telecommunications and safety installations) are therefore planned based on the experience of the planner and today's state of the art technology that does not differentiate sufficiently between RES's for different applications and in different locations.

This report describes detailed recommendations for batteries in RES's and presents the method for making specific recommendations yet avoiding the difficulty and cost of a detailed analysis for each system. The approach is based on creating categories of RES's that are characterized by similar conditions of use for the component under investigation. The batteries component usually accounts for the largest share of the lifecycle cost of an RES (Sauer 2003), so the method has been developed for batteries but can be extended to other components as well. For each category, specific recommendations can then be made in terms of type and other technical features of batteries, test procedures relevant to the category, operating regimes, etc. A benchmarking process is then possible that allows battery manufacturers, planners, and users to determine which product is particularly suitable for a specific category of RES's.

Figure 1 describes the process through which batteries and their use can be assessed and proper recommendations provided. This same process could be used to assess other system components.

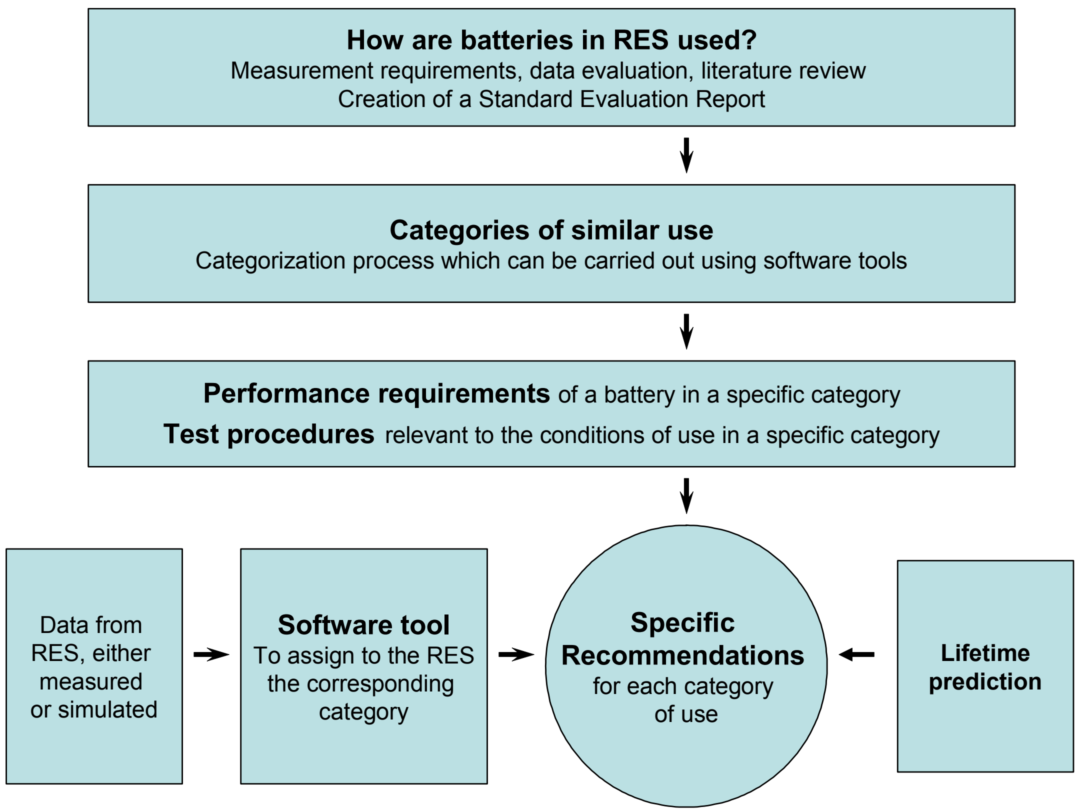

Figure 1: Schematic diagram showing the project structure

During the project it became necessary to refine some existing concepts and develop new ones. The following questions had to be answered:

1. How are batteries used in RES's?
2. How can categories of similar use be defined and derived from RES data?
3. How can a category of similar use be assigned to an installed system (i.e., very detailed data are available or only highly aggregated data exist) or a planned system (i.e., no data of the operation or only simulated data are available)?
4. What are the performance requirements of a battery in a certain category, and what procedures can be used to provide a meaningful test concerning the performance requirements in that category?
5. Is it possible to predict a battery's lifetime using models so that detailed recommendations can be made before test results become available for batteries offered for RES's?

These individual steps will be explained in detail.

3. The use of batteries and other components in renewable energy systems

This chapter contains background information on the creation of a public database (www.benchmarking.eu.org) on RES components and operation. In addition, it describes how the information in the database can be used to analyze a specific RES and the conditions of use of its components.

3.1. Publicly available information

The scientific literature contains a wealth of information on using RES components on encountered problems and on the expected lifetime of products. A detailed analysis has been published (Tselepis et al. 2004) and is available in a Benchmarking project report by Tselepis and Nickoletatos (2003). This analysis provides useful insight but, not surprisingly, it does not provide information that can be used for making specific recommendations. Many authors have investigated different systems in different locations, with different products and operating regimes, but each author has used his/her own method of analysis, focused on a specific topic of interest, and based their findings on the data that were available to them. The list of references provided by Tselepis and Nickoletatos (2003) shows that the review of the scientific literature was very comprehensive.

The issue of an end-of-life criterion of batteries also underlines the main difference between batteries and other components. Batteries usually degrade slowly and can often sustain part of the required function for a long time, even if the capacity has declined considerably. Other components fail quickly once a fault develops and often do not show any significant degradation during their lifetime (for instance, charge controllers or inverters).

The question of how batteries and other components are used in RES's therefore has to be answered by analyzing RES data.

3.2. Data analysis

The first step to assess a specific RES component, in this case batteries, was to analyze data and experience for batteries used in such power systems.

Minimum requirements for measurement procedures

It is obvious that comprehensive data have to be available for a detailed analysis of the operating conditions of a battery or any of the other components. Highly aggregated data, such as the yearly or monthly energy throughput, is of interest for certain types of analysis but is inadequate. The state of charge (SOC) of a battery and its variation over time is probably the parameter that influences the lifetime of a battery more than any other parameter and has to be available if the operating conditions are to be understood. However, calculating the SOC value requires a good time resolution of the data; hourly data at least have to be available. Therefore, minimum requirements for data acquisition had to be defined. These requirements were defined in a document in a project document (Baring-Gould 2002) for all components in an RES. The guiding concept was: What information does an expert require to make an in-depth analysis of the system and an individual component? Only data sets that fulfil this requirement are capable of providing the depth of information required for making detailed recommendations.

Information concerning analyzed RES's

For the categorization process described in Section 4, 146 data sets were available for which a sufficiently detailed data acquisition had been carried out for a representative time period (in RES's, this is often 1 year due to seasonal changes of the renewable energy resources and loads). Table 1 provides an overview of the RES. RES's with insufficient data availability or inconsistencies (e.g., energy consumption greater than energy supply for the period under investigation) were excluded and are not contained in Table 1. The table only lists research installations if their loads and energy supply are a realistic approximation of real conditions.

Table 1: Overview of data sets used for the categorization process (further data sets became available subsequent to the categorization process, and a total of 254 data sets from 144 RES's are currently available in the database, www.benchmarking.eu.org)

Type of system	Number of data sets	Location in Europe	Location in America	Location in Asia	Number of systems
PV/battery	109	81	3	25	31
PV/diesel generator/battery	69	69	-	-	15
Wind/battery	-	-	-	-	-
Wind/diesel generator/battery	-	-	-	-	-
PV/wind/battery	-	-	-	-	-
PV/wind/diesel generator/battery	6	6	-	-	1
Other RES	-	-	-	-	-

These data sets form the basis of the further work described here. It is believed that this list includes the majority of all data sets and RES's that fulfil the minimum requirements (Baring-Gould 2002) (i.e., for which sufficient data are available for a sufficient time).

Data evaluation tool ITHESA

The differences in data from different data acquisition systems are large. The point of measurement (e.g., measuring the load before or after the inverter), the time stamp, the averaging methods used (in particular for the battery current and voltage), and the format for storing data have to be taken into account. As a result, the software program ITHESA, created to evaluate the data, had to be very flexible. ITHESA can handle all reasonable methods of data acquisition and data formats but also requires the user to provide detailed information about the data structure. The preparation for data input is necessarily complex. ITHESA contains an online help function, but in addition, a short description of how the system is used is contained in the annex.

ITHESA is publicly available under www.benchmarking.eu.org, and it is hoped that it will set the standard for evaluating data of RES components whenever an in-depth analysis with high-quality data is required.

Standard Evaluation Report

Comparing systems is easiest if the data are presented in a standardized manner. For this reason, the Standard Evaluation Report (SER) has been created for all further analysis (Perujo 2003 and Sauer et al. 2003a). The report allows the evaluation of the whole system and its main components: PV generators, wind generators, biomass and/or diesel generators, micro-hydro generators, batteries, loads, and inverters.

The aim of the SER is to present the results in such a way that the operation of a component in different systems can be easily compared.

- All component measurements are normalized to make comparisons easier; for example, battery currents are given as I_{10} and battery voltage per cell.

- Histograms and graphs highlight those aspects of operation that are most critical and are usually used when analyzing RES's and their components.
- The format for each graph or other representation is specified to make comparisons easier.
- RES data covering more than 1 year have been subdivided into individual data sets, each covering a period of 1 year.

For the system as a whole, all technical information on the system and the components, geographical location and layout, climatic conditions, the overall energy balance, and the performance figures (such as loss of load and time with restricted power capability) are provided whenever the data allow this. It should be stressed that even among the carefully selected RES's with high-quality data, all information is not available. Nevertheless, it is important to structure the SER in such a way that a complete system analysis is possible if all data were available.

4. Creating categories of similar use

The creation of categories of similar use for making detailed recommendations and for benchmarking components concerning their suitability for specific RES's is at the heart of project work discussed in this report. Without the creation of such categories, no distinction would be possible between batteries with high annual energy throughput and a daily full charge and batteries for systems with many days of autonomy, a very low annual energy throughput, and periods of months without a full charge. Figure 2 shows the time series of SOC for two different RES's (Sauer et al. 1997), which obviously require different batteries (Sauer et al. 1997a). Sauer et al. (1997) were the first to analyze data and look for different RES categories. Their work provided the rationale for creating categories of similar use and the certainty that categories could be created considering all RES systems architecture, applications, and locations in different continents. The categorization process is described fully by Svoboda (2003) and Wenzl et al. (2005).

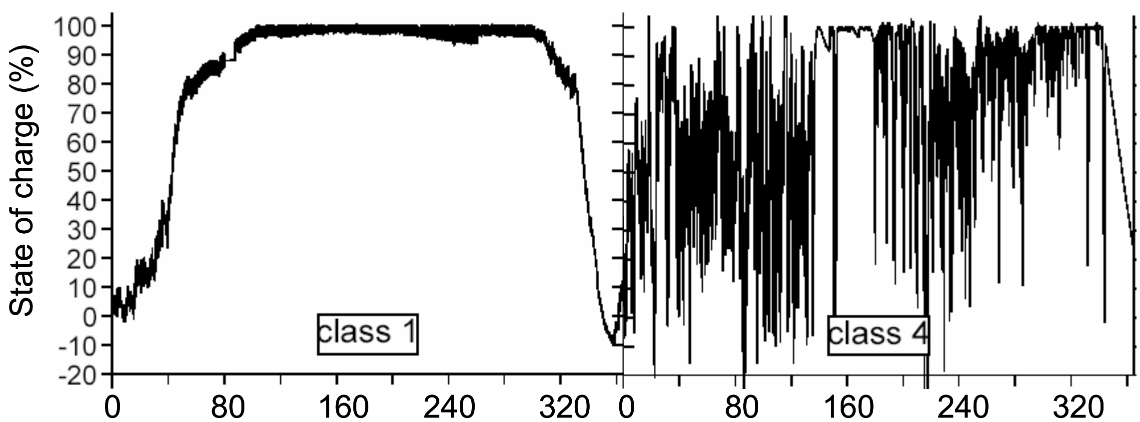

Figure 2: Time series of state-of-charge of two RES's (Sauer et al, 1997) showing large differences in the way that batteries are used. Left: lamp for bus shelter; right: mountain refuge in the German Alps

4.1. Definition of suitability in terms of fulfilling performance requirements and achieving a high lifetime

There are many different criteria for classifying RES's, such as systems architecture, size, use of renewable energy resource, etc. For the purpose of selecting a component for an RES, criteria describing the suitability of the product for the system must be used. An inappropriately chosen battery type or a battery of poor quality will soon fail, whereas a suitable battery will continue to fulfil the performance requirements for much longer. The size of the battery and the operating regime chosen for the RES influence the lifetime of the battery in both cases; however, under identical conditions a suitable battery will always have a longer life. Suitability of the battery or any other component therefore needs to be defined in terms of ability to fulfil the required performance levels as long as possible. At this stage, the economic assessment of lifetime versus cost is not included in the categorization process and, for the purpose of categorization only, the assumption is made that the battery with the highest lifetime is also the most cost-efficient battery. When making recommendations, this assumption will be qualified. However, the advent of better battery life assessment methods, as described in Section 6, will eventually allow this comparison to be made.

Recent papers (Meissner 2004, Wenzl et al. 2004) offered an analysis of what lifetime and performance prediction mean. End of lifetime is reached if the state vector of performance (Meissner 2004) no longer lies within the acceptable range of values. A vector rather than a scalar value of performance needs to be used because it is too simplistic to tie end of lifetime to one performance value (in most cases, capacity). Other performance requirements whose values can also lead to the battery no longer being able to fulfil the performance requirements are self-discharge, charge acceptance, high rate power capability at medium SOC and low temperature, energy requirement during charging, and cost of energy delivered in systems with auxiliary energy generation. Figure 3 shows a schematic diagram of such a state vector as a radar plot. In RES's it is important not to use the usual value of 80% or 60% of capacity as the only performance indicator for end of life because often the optimum replacement time should be at a much lower residual capacity. Further information is provided by Tselepis and Nickoletatos (2003).

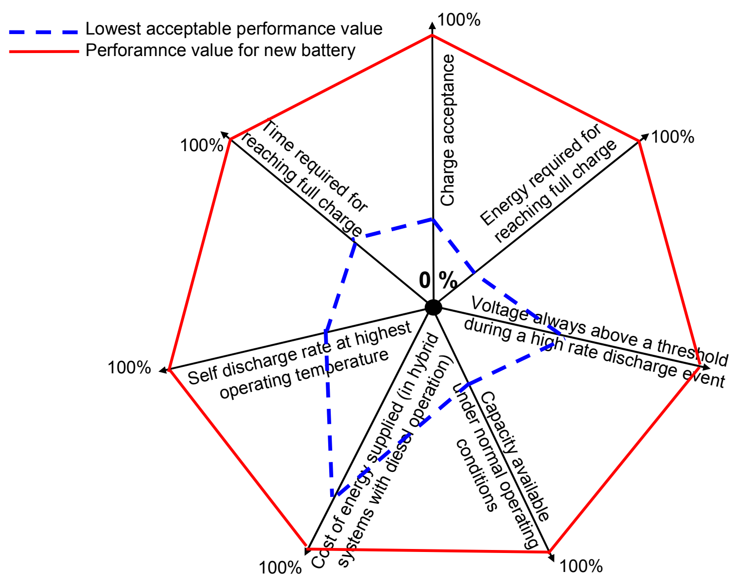

Figure 3: Schematic diagram showing the end-of-lifetime definition using the concept of a state vector of performance values. The number of dimensions and the performance values that they represent, as well as the respective minimum values, are application specific

4.2. Definition of stress factors

A number of stress factors, statistical parameters derived from the time series of voltage, current, temperature, and SOC reflecting operating conditions generally used and accepted as relevant for the lifetime of a battery, had been defined as part of the Benchmarking project work. Ultimately only eight stress factors have been chosen for the definition of categories (Tables 2 and 3) (Svoboda 2003). Of the eight factors chosen, two are related to battery temperature, which is fairly independent of all the other stress factors. In line with Sauer et al. (1997), temperature is therefore considered a separate dimension of the categorization process, and its implications apply to each category.

A detailed description of the stress factors and the reasons for their choice is given by Svoboda (2003) and Wenzl et al. (2005).

Table 2: Definition of stress factors that have been chosen for the categorization process and assignment to intensity levels. The stress factors as a result of temperature are contained in Table 3

Stress Factor	***Description***
TIME BETWEEN FULL CHARGE	Average time between recharging the battery to a SOC above 90% *
CHARGE FACTOR	Average charge factor per year
DISCHARGE RATE	Highest average current at which 1% of the Ah throughput was discharged
AH THROUGHPUT	Cumulative Ah throughput per year
LOW STATE OF CHARGE	Cumulative operation time of a year at SOC <35%
PARTIAL CYCLING (Cycling in partial State of Charge)	Weighted Ah throughput in a given SOC range, expressed in a single Partial Cycle value

*: A value of 90 % is chosen because the calculation of the SOC is not very accurate above 90%. Also, in some RES's, higher SOC than 90% may never occur due to the system setting.

Table 3: Definition of temperature stress factors chosen for the process and assignment to intensity levels

TEMPERATURE ACCELERATION FACTOR	Temperature acceleration factor, which is based on the assumption that a 10°C temperature increase reduces the lifetime by a factor of 2.
LOW BATTERY ENVIRONMENTAL TEMPERATURE	The lowest operating battery temperature maintained for at least 12 hours (average over a 12-hour period).

Each stress factor has a numerical value calculated from the data used in the SER using the definitions of Tables 2 and 3. The detailed mathematical definitions are given in the paper by Wenzl et al. (2005) and the final project document available on the project Web site, www.benchmarking.eu.org.

4.3. Assigning sets of stress factors of batteries to categories of similar use

Each RES can now be depicted in a radar plot (Figure 4) showing the intensity levels of the stress factors as a six-dimensional vector. By comparing the radar plots of the various SERs, it became clear that the RES under evaluation could be categorized into six groups. RES's within a group have a similar vector of stress factors and therefore are subject to a similar combination of intensity levels of stress factors (Svoboda 2003). These groups are termed categories. Where only narrow bands of intensity levels per stress factors were defined, these stress factors are most important in describing the category of use. A broader band means that this stress factor seemed of less importance for that particular category. Figure 5 shows the radar plots of each category. RES's whose vector of stress factors falls into the allowed bands belong to the same category. The six categories are described in detail in the next section.

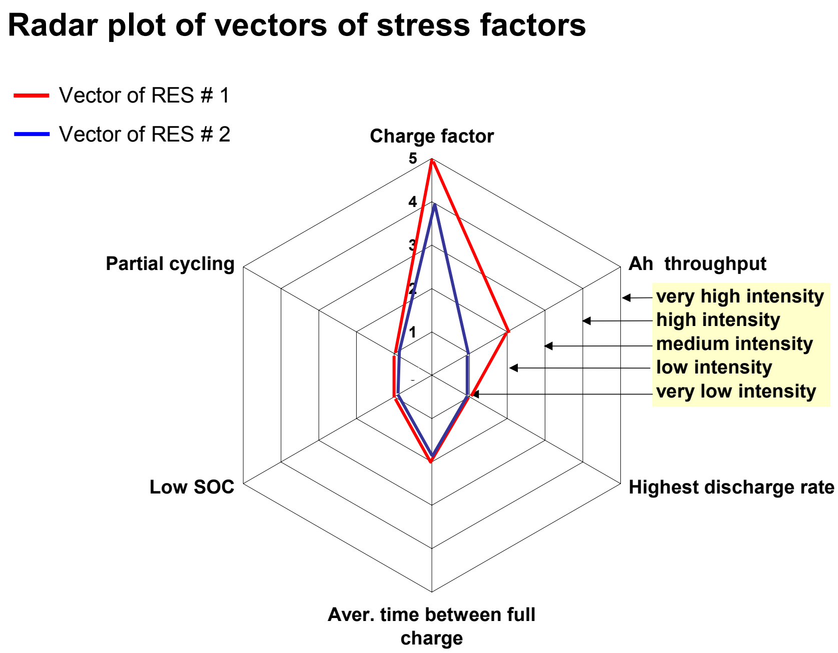

Figure 4: Radar plot of vector of stress factors for two RES's

For each of these six categories, the two temperature stress factors are an additional dimension. An RES is therefore characterized by its assignment to one of six categories and by the assignment to a high temperature and low temperature stress factor.

Obviously, it does not make sense to describe a category in this manner if the category can be recognized as the result of poor planning or poor choice of operating regime. Also, categories that show abusive conditions for the battery have to be investigated further and their relevance must be determined. However, categories have to be considered in which abusive conditions are in line with good planning principles and cost-effective operating regimes lead, for example, to long periods without a full charge or long periods of cycling in a partial SOC. Fortunately, none of the categories found by means of the process described above seemed to be the result of poor planning or poor product quality.

This categorization method achieves an integral approach to classification that does not focus on one type of stress factor but takes all of them and their interdependence equally into account. In addition, this method allows an automatic categorization process (Nieuwenhout et al. 2005a), as described in Chapter 7. This is extremely important because it leads to an objective and low-cost assignment of an RES to a category. An analysis of an existing or planned system by an expert with a subsequent assignment of the category is clearly impractical and far too expensive.

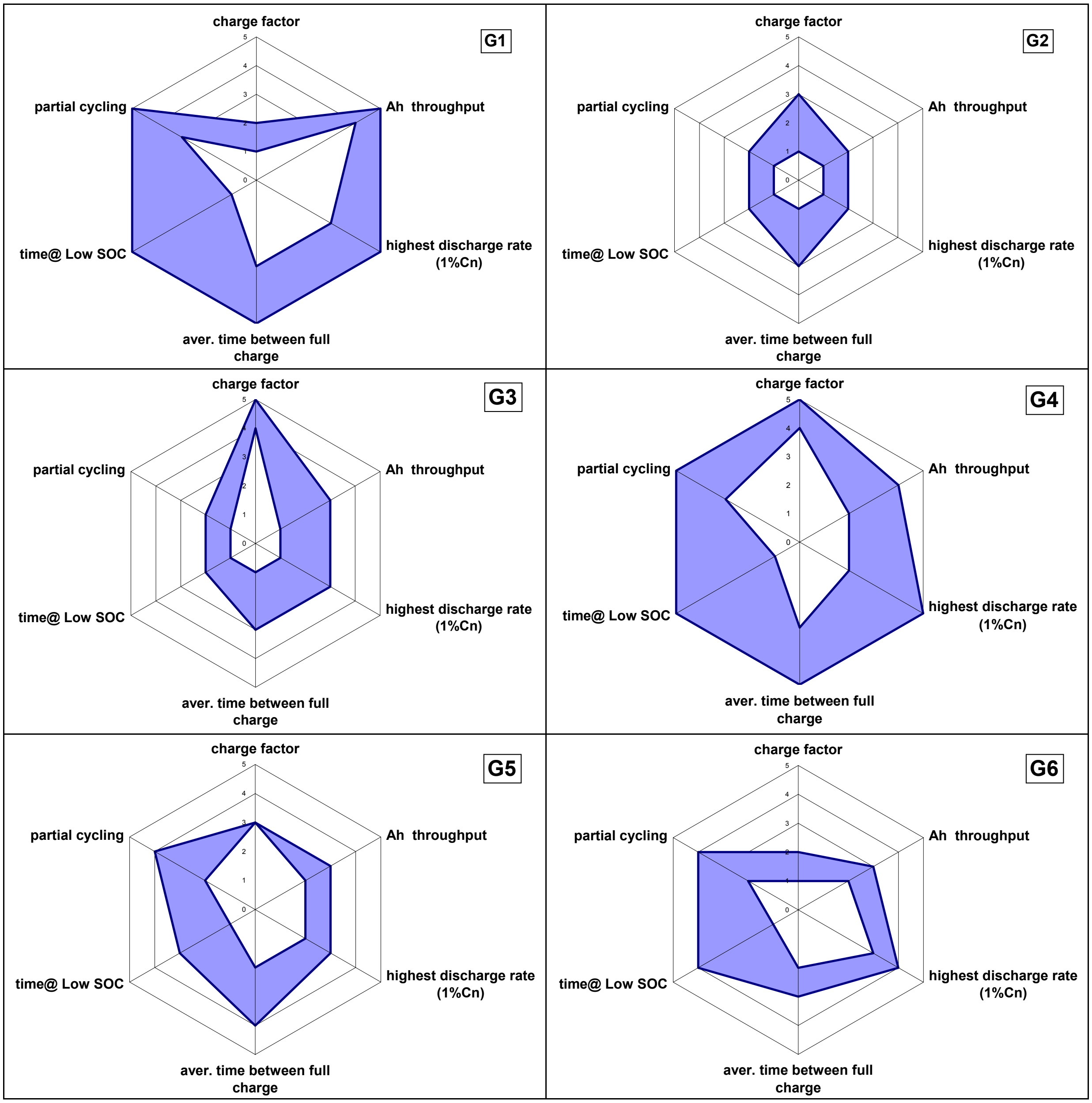

Figure 5: Graphical representation of the six categories that are defined based on the intensity levels of stress factors. The shaded range indicates the intensity levels that define the category

4.4. Description of the performance requirements of categories

The following is a short description of the performance requirements for each category. A more detailed description is contained in the report by Svoboda (2004a).

Category 1 – RES with undersized generation capacity and deep cycle operation
The typical operation of such an RES can be characterized as cyclic operation with relatively full cycles and deep discharging of the battery. The charge factor is low, and a full recharge happens relatively seldom. The battery may also be operated for long periods in a discharged state below the level of 35% SOC. However, the exact intensity level of this stress factor has not been considered to be important when considering the intensity levels of the other stress factors. Batteries in RES's were considered to have the same combination of stress factors even if the stress factor of time at low SOC was very different. The RES battery operates often at partial SOC and at a high discharge rate.

The aging mechanisms with high risk may cause relatively fast fading of the power performance. The battery may soon start to have an influence on the RES performance due to medium to high discharge currents. Also, as a capacity fade usually appears in parallel to a power fade, the energy availability of the battery will soon limit the RES performance as well.

Due to the limited recharge and deep discharging at a relatively high current rate, the SOC of the individual cells can develop noticeable differences. The weakest cells may reverse polarity during discharging, particularly in the case of higher voltage batteries (many cells in series). Reverse polarization of a cell accelerates aging dramatically and limits the battery performance.

In the case of a low environmental temperature (low environmental temperature factor is high), electrolyte freezing may happen due to deep discharge conditions (possibly long time at a low SOC and electrolyte stratification). The electrolyte above the electrodes under such conditions can have a density considerably below 1.1, even if the SOC of the battery is in an acceptable range.

Category 2 – RES with undersized generation capacity and shallow cycle operation
The typical operation of an RES of Category 2 is characterized by a low Ah throughput at a high SOC and frequent full charges (however, with very limited generation capacity).

The main problem for a battery in this category is the charge factor. In flooded batteries, the charge factor of intensity level 3 will only barely be adequate to maintain a full charge, and in intensity levels 1 and 2, a slow decrease of capacity can be expected because the battery will be slowly discharged. If occasional deep discharges occur, such as for winter, exceptional climatic conditions or user requirements, then a full recharge will take a long time. Acid stratification will not be removed regularly unless a charge controller with a high voltage limit for such an occurrence is used. The use of VRLA batteries will significantly reduce these risks and are therefore highly recommended for applications in this category. However, even for VRLA batteries, the charge factor of intensity level 1 is too low.

Category 3 – Application with shallow cycling in combination with overcharge
The typical operation of an RES of the category 3 is characterized as a very-low-to-medium Ah-throughput operation. The battery is charged with a high-to-very-high charge factor, and full recharge usually happens often.

In this category, the corrosion process is accelerated by a very high charge factor (high charge voltage), which can also be the result of high operating temperature and the lack of temperature compensation of the charging voltage. High charge factor/high charge voltage may lead to high gassing that accelerates AM shedding. The very high risk of corrosion and the high risk of shedding may lead to an internal short circuit and a sudden death of the battery. The high gassing results in a very high risk of water loss in flooded batteries, which may cause maintenance problems and drying out of VRLA batteries. This in turn may increase the internal resistance, reduce the reaction kinetics, produce excessive amount of gas released from the battery, and cause other effects leading to a reduction of power performance and capacity. The very high charge factor in the case of VRLA batteries may lead also to thermal runaway. A resulting high battery temperature also accelerates degradation of the AM.

Category 4 – Deep cycling application in combination with seldom but strong charge
The typical operation of batteries in category 4 is characterized as a medium- to high-throughput operation at high partial state of charge (PSOC) cycling. A full charge happens with a medium frequency or very seldom. When a full charge happens, then the charge factor is very high. The battery may stay for longer time at a very low SOC. The discharge rate may be high.

Due to infrequent full recharging and partial SOC operation, the category may be associated with a high risk of electrolyte stratification. Electrolyte stratification is only reduced by the very high charge factor and fully removed if the recharging phase is very long. Additionally, even through providing a higher charge factor, it is unlikely that hard/irreversible sulphation at the bottom at the electrodes can be fully converted during recharging events. Hard/irreversible sulphation is therefore evaluated in this category as a medium risk. A full charge with a high charge factor leads on the one hand to a high risk of corrosion and water loss in flooded batteries, for VRLA batteries to drying out and thermal runway. On the other hand, a full recharge with a high charge factor reduces the rate with which hard/irreversible sulphation forms and also effectively removes electrolyte stratification. The battery operating conditions of this category lead to a very high risk of active material shedding. AM shedding under these operating conditions is accelerated mainly due to the PSOC cycling, higher Ah throughput, a full charge with a very high charge factor and possibly higher currents.

The aging mechanism that dominates in a battery operation of this category depends on the battery type and quality. An electrolyte circulation system or the use of VRLA batteries is recommended. Heat dissipation from the battery during charging with a high charge factor should also be a concern, particularly in a high temperature environment.

Category 5 – Optimal RES
The typical battery operation in this category is characterized as a low to medium throughput operation without a deep discharge and resting in a discharged state. The charge is realized by a medium charge factor; the average time between full charge and the partial cycling factor can vary in a range from low to high. These factors indicate that the batteries in this category may operate at a high to medium SOC range. The highest discharge rate is low to medium.

The risk of hard/irreversible sulphation, AM degradation, and electrolyte stratification is medium. While there is not a high Ah throughput and the battery is not usually fully discharged, neither does the battery rest for a long time at low SOC. The battery operation in this category seems to be well optimized.

A combination of different aging mechanisms limiting the battery performance in a real application of this category can be expected. The dominating mechanisms in a real operation depend on the battery type and quality. The capacity and power fading are expected gradual.

Category 6 – Application with limited charge
The operation of a battery in this category may be characterized as a low to medium Ah throughput. The PSOC factor varies in the range from low to high, thus PSOC cycling can be expected also in the medium SOC range. The charge factor is very low to low. There may be some period of time when the battery operates or rests in a very low state of charge. The frequency of the full charge is medium.

Such operation indicates a high risk of hard/irreversible sulphation and electrolyte stratification, and there is a medium risk of AM degradation. Due to the low charge factor, electrolyte stratification will not be effectively removed.

The dominating degradation mechanisms can be expected to lead to fairly quick fading of the power performance and the capacity. The slope of the capacity and the power fading depends on the battery type and quality. In batteries designed for PSOC operation and low charge factor, the slope may be very low. VRLA batteries are a much better choice for this category than flooded batteries.

Application of categorization process for other components

The categorization process has also been applied to wind turbines (Peterschmidt 2004) to determine whether the concept can be used for other components. It was clearly shown that the process can be used for other components if the SER contains all relevant information.

- For small wind turbines, for instance, a frequent change of wind direction can cause premature failure of the wind turbines. This information is not included in the present SER even if the data for it existed.
- For generators, it is important to know the number of generator starts, the temperature when starting, and the average run time, regardless of whether the fuel is a biofuel or a fossil fuel. This information is relevant to a generator's lifetime and might be important when selecting the most suitable generator for an RES.
- Inverters are usually optimized for high efficiency at their nominal power. Data demonstrate clearly that there may be RES's in which the inverter is operated most of the time at a low power output, and the efficiency under these use conditions may be much more important than the efficiency at nominal power.

When using the categorization process for other components, it is therefore important to analyze that component's stress factors and aging mechanisms and to consider all aspects of operation.

5. Performance requirements and test procedures

Benchmarking is a process in which components from different manufacturers and of different designs are compared using identical test conditions. Obviously only results of test conditions that are relevant to the conditions of use should be compared; results of other test procedures provide only limited information concerning the suitability of a product for the later application.

5.1. Performance requirements

For each category, performance requirements such as the capability of achieving a high Ah throughput, operating at partial SOC without degradation, withstanding a low charge factor, etc. have to be described (Svoboda 2004a). Some of the performance requirements can be easily and directly deduced from the categories, but a full description of the performance requirements of the batteries in each category and the test procedures for them is not possible when restricting the discussion to the performance requirements that can be easily deduced from the categories.

It is useful to introduce the concepts "risk of aging processes and loss of performance," which are likely to take place, and "damaging conditions," which may develop, so that recommendations can be made. Damaging conditions that need to be considered are acid stratification, risk of freezing of the electrolyte, and reverse polarization during discharging.

It is important to distinguish between the risk of aging processes and loss of performance, which is the result of the combination of stress factors in a certain category, and the aging mechanisms. Corrosion is a good example to explain the concepts. The aging mechanism corrosion during float charging is well understood as a function of voltage and temperature. However, the loss of material from corrosion of the positive grid, measured in $mg/mm^2/h$, depends among other things on the alloys used and the manufacturing process of the grid (e.g., type of casting and manufacturing quality). Identical corrosive conditions will therefore lead to massive corrosion in one battery and insignificant corrosion in another battery. In addition, the same amount of corrosion (thickness of corrosion layer and/or quantity of material which has corroded) does not necessarily lead to the same loss of performance because the thickness of the grid also plays a role. Heavy-duty batteries with thick positive grids will still have a functional grid when starter batteries optimized for starting no longer have a grid because of the complete conversion of lead to lead dioxide. Test procedures only determine the loss of performance as an integral measure and therefore can only determine whether the risk of an aging process has indeed resulted in a performance loss via the aging mechanism.

Table 4 (Svoboda 2004a) shows an assignment of aging risks to categories as a result of the combination of the various stress factors. This assignment is an expert opinion based on experience gained with batteries in RES's. There simply are not enough batteries from well-monitored systems with subsequent post-mortem analysis to base Table 4 on experimental results. A table (Figure 6 in Section 5.3) with a similar structure has been provided (Desmettre et al. 2000) that matches common battery test procedures for different types of lead acid batteries to aging mechanisms. The aging mechanisms were observed as a result of a post-mortem analysis following laboratory tests.

Table 4: The table shows an assignment of aging risks to categories as a result of the combination of the various stress factors. This assignment is an expert opinion based on experience gained with batteries in RES's. The value 5 indicates a high risk, and the value 1 indicates a low risk

	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Cat 6
Corrosion	1	4	5	4	1	1
Sulphation	5	1	1	4	3	4
AM degradation	5	1	3	5	3	3
Stratification	5	1	1	4	3	4

5.2. Test procedures for benchmarking batteries in RES's

There are a number of possibilities of matching test procedures to applications:

1. Experience-based test procedures
2. Test conditions that resemble well-defined operating conditions
3. Test conditions that try to accelerate one aging mechanism
4. Test conditions that simulate the complex combinations of operating conditions and the vector of stress factors found in the application
5. Test conditions that try to create the same combination of aging mechanisms found in RES's.

It is obvious that the first two options cannot be used for RES's, and the third option has only limited use, even if realistic test procedures could be developed. Batteries in RES's usually fail because of a combination of aging effects, and test procedures focusing only on one aging mechanism can therefore only be used for those categories of RES's in which one aging effect dominates all others. As the description in Sections 4.1 and 4.2 has shown, such categories were not found to exist.

Concerning the fourth option, Mattera et al. (2003) describe the difficulties encountered when trying to match the operating conditions of batteries in RES's to proposed test procedures. The process of matching was based on the histograms of SOC and current intensity and the Fourier transform of current intensity. The results were satisfactory for defining a test procedure for RES's with wind generation but were unsuccessful for RES's with PV generation. The concepts described by Mattera et al. (2003) were explored further, and an attempt was made to match the operating conditions of batteries during tests to the operating conditions of batteries in RES's. For instance, the current voltage profile of a battery under test can be used as an input to the software ITHESA, which calculates the SER and the stress factors of the system. This attempt has failed predominantly because of a fundamental problem. Test procedures for batteries are by necessity accelerated; the operating conditions reflect this and thus the stress vectors have to be different. Also certain stress factors only reveal their potential for accelerating the aging mechanism if they exist for a long time (e.g., time at low

SOC). Under accelerated test conditions, this stress factor is unlikely to have a relevant impact on the lifetime. Svoboda (2004a) provides full details of why this fourth option had to be abandoned.

The remaining option is the use of test conditions that create the same combination of aging effects as those found in RES's. Similar combinations of aging effects under test conditions and real operating conditions mean that the different combinations of stress factors that exist in laboratory tests and field applications interact in such a way that their integral effect at the end of lifetime is the same.

Definition of test procedures based on similar combinations of aging effects

Table 4 shows the aging effects that are expected for each of the six categories that have been found. This table has been compared to the results of test procedures in which a post-mortem analysis has been carried out (Desmettre et al. 2000). These results are reproduced here for easier comparison (Figure 6). Different terms and scales to describe aging have been used in Figure 6, compared to those used in Table 4. Desmettre et al. (2000) used a four-level intensity scale and considered acid stratification an aging mechanism. Shedding and loss of active mass surface were combined into the term "softening," and drying out was not considered. Despite this, the two results are comparable. A correlation (see Table 5) of the aging risks that can be expected in a certain category (Table 4) and the aging observed as a result of test procedures (Figure 6) is now possible. This correlation is independent of the way the two scales are combined. The comparison shows that certain test procedures lead to exactly that combination of aging risks that can be expected in a certain category (Ruddell 2005). Such test procedures can now be ascertained to be relevant to the category. These seven test procedures are described in detail by Desmettre et al. (2000).

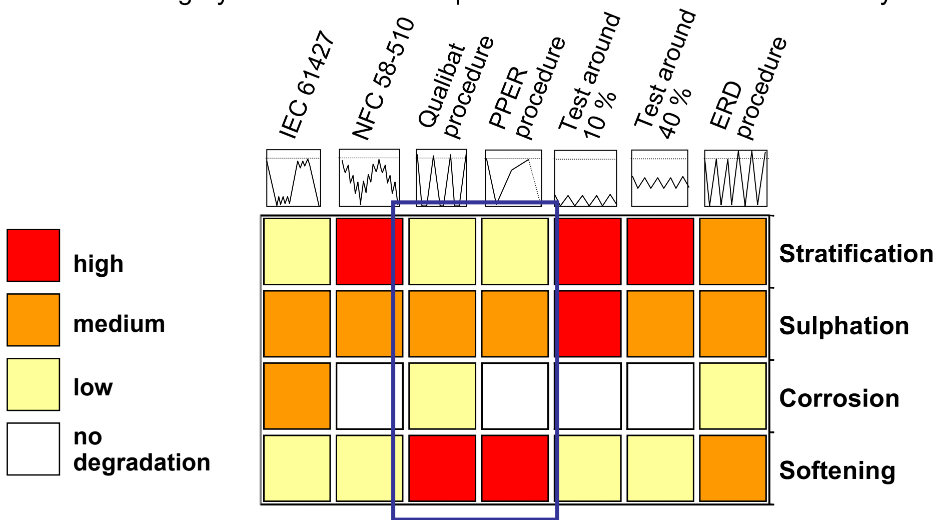

Figure 6: Results of post-mortem analysis of batteries that had been tested until end of life by means of different test procedures (reproduced from Desmettre et al. 2000)

It can be seen that results of the IEC test 61427 can be expected to be highly relevant to batteries used in RES of category G2, whereas the test results will probably be of little relevance to batteries used in category 1 and category 5 systems.

It is not surprising that existing test procedures will match at least some categories. After all, test procedures for RES's are defined by experts so that they match the operating conditions of batteries in RES's. Identical patterns of aging effects mean that the tests simulate the overall effects of real operating conditions. Because different types of batteries in tests show the same combination of aging effects when they fail, it can also be expected that both inappropriate and suitable batteries fail from the same combination of aging effects in real applications.

Table 5: Correlation coefficients between the aging risks that can be expected in each category and the aging mechanisms observed by post-mortem analysis in batteries for which lifetime tests have been made using the seven test procedures at the top of the table. Combinations with a particularly high correlation coefficient are marked

	IEC 61427	NFC58-510	PPER	QUALIBAT	~ 10% SOC	~ 40% SOC	DRE
Category 1	-0.96	0.80	0.74	0.70	0.79	0.83	**0.95**
Category 2	**0.96**	-0.80	-0.74	-0.70	-0.79	-0.83	-0.95
Category 3	**0.74**	-0.96	-0.39	-0.27	-0.97	-0.95	-0.67
Category 4	-0.50	-0.25	0.72	**0.89**	-0.28	-0.16	0.61
Category 5	-0.96	0.80	0.74	0.70	0.79	0.83	**0.95**
Category 6	-0.85	**0.93**	0.53	0.43	**0.93**	**0.94**	0.79

Table 6 shows which test procedures should be used to benchmark batteries for each category of use. This table is part of the specific recommendations for planners, manufacturers, and users. Until test results using the proposed new test procedure become available, batteries that achieve good results in both of those tests or the tests highlighted in Table 5 should be given preference over other batteries for use in the respective categories.

Table 6: Assignment of test procedures to categories

Category 1	NFC58-510 plus PPER (Combined test procedure, aging ratio 1:1)
Category 2	IEC61427
Category 3	IEC61427 plus Qualibat (Combined test procedure, aging ratio 1:0.3)
Category 4	IEC61427 plus Qualibat (Combined test procedure, aging ratio 1:1.5)
Category 5	NFC58-510 plus PPER (Combined test procedure, aging ratio 1:1)
Category 6	NFC58-510 plus PPER (Combined test procedure, aging ratio 1:1)

6. Lifetime models

Matching test procedures to categories allows specific recommendations and the establishment of a benchmarking process as soon as all batteries which manufacturers consider suitable for RES's have been tested. However, for the following reasons (see also Wenzl et al. 2004), it is desirable to also base recommendations on simulations of battery lifetime:

- The test procedures given in Tables 5 and 6 as best test procedures have not been carried out for many batteries, and it will take time until manufacturers accept the need for these test procedures.
- For newly developed batteries, it seems inappropriate to wait until the tests for the renewable energy market (a small market for lead acid batteries) have been carried out. A quicker assessment of the suitability of newly developed batteries is therefore desirable.
- Changes in the operating regimes and their effects on battery lifetime can only be investigated by means of models.
- Any recommendations for systems that do not exactly match a category will be more accurate if based on lifetime models.
- Although categories of use may be used to predict expected battery life, variations of use within each category will also impact battery life, something that can only be assessed through the use of a model.

This chapter describes work on lifetime models which has been carried out and lifetime tests of batteries which were carried out to verify the models.

6.1. Lifetime tests

To provide credibility for users, lifetime tests need to resemble the operating conditions of interest to the users. It is well known that batteries in some wind applications have a much shorter life than expected and shorter than in PV applications. However, existing test profiles do not reflect the conditions found in wind systems, such as higher rates and fast fluctuations of current. Additionally, lifetime prediction models can only be verified if test results are available that are sufficiently different from the tests that are used to parameterize the models. To address this issue, two use profiles were developed based on data from operating power systems to verify that the lifetime models reflect PV and wind applications (Mattera et al. 2003). The process of finding test conditions with similarity to the operating conditions is by no means simple and is described in detail by Mattera et al. (2003). The resulting test procedures for both PV and wind systems are shown in Figure 7. The tests were carried out for two types of batteries: flooded batteries with tubular plates and flooded batteries with flat plates. Details of the tests and test results can be found in the report by Mattera (2005). These test procedures are sufficiently different from the standard tests that were used to parameterize the batteries for the models. As of this writing, only two of the expected tests have been completed, so the following results are based on limited data and will be refined as more data become available.

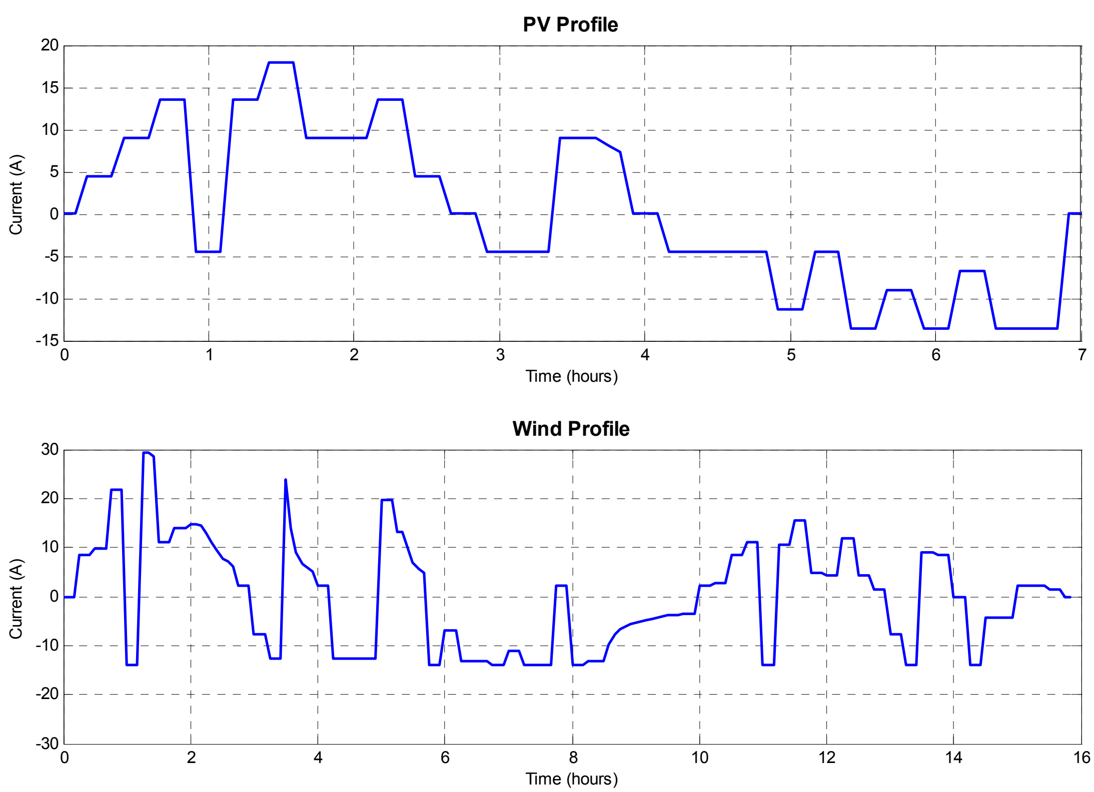

Figure 7: Battery use profiles for battery life testing of PV and wind hybrid systems

6.2. Battery lifetime models

Throughout the project two existing lifetime prediction models have been improved and evaluated for their accuracy in predicting the life of lead acid batteries. The two methodologies are:

- Cycle-counting method (Manwell et al. 1998): This is based on the cycle to failure curve, which most battery manufacturers supply as part of their technical documentation for batteries. An updated version of this model has been developed in which a cycle, defined as a discharge and charge event, is evaluated as to the SOC at which the cycle takes place and matched to the numbers of cycles that the battery can tolerate until it fails. Each discharge charge event thus uses up a proportion of the battery lifetime dependent on the average SOC and depth of discharge during that discharge charge event (Bindner 2004).
- Weighted Ah-model (Puls and Sauer 1996): The voltage of the battery during charging and discharging is modeled using a Shepherd-type voltage model. Corrosion depending on the voltage is calculated, resulting in an increase in internal resistance and a loss of capacity. Capacity is also lost through Ah throughput decreasing the active mass available. Two Ah-weighting factors are included in the analysis: time at low SOC and acid stratification. These weighting factors can be associated with sulphation.

A full description of the work is given by Bindner et al. (2004).

The results of comparisons between the tests discussed in Section 6.1 and simulations using the lifetime prediction models are discussed below. Tables 7 and 8 below show that the lifetime results and the simulations lead in fact to similar results even if the absolute values are incorrect. However, a battery and a profile with a longer lifetime in the simulation also have a longer lifetime in the lifetime tests.

Table 7: Results of FhG/Risoe Weighted Ah-Throughput Model

Battery & Profile	Simulation Lifetime (days)	Test Lifetime (days)
OGi1 PV	660	239
OGi2 Wind	425 (64% of PV profile)	174 (73% of PV profile)
OPz1 PV	830	600+*
Opz3 Wind	633 (76% of PV profile)	400* (66 % of PV profile)

** = estimated lifetime (test not yet complete)*

Table 8: UMass Cycle Counting Model

	Experiment	Original Simulation	Improved Simulation	Life Curve Adjustment Factor
OGi Wind profile	0.33	0.72	0.33	0.043
OPzS Wind profile	1.0	1.74	1.0	0.11
OGi PV profile	0.66	1.24	0.62	0.043
OPzS PV profile	N/A**	2.89	2.05	0.11

***Data are not available. Tests are ongoing.*

Clearly, the cycle counting model, despite its simplicity, shows a good prediction. This is necessarily the case for one of the test profiles because the "life curve adjustment factor" as a parameter is fitted in such a way that simulation and lifetime results are identical. However, using the same factor, the results for another test are very close. The weighted Ah-model also shows a good prediction despite its complexity and the number of included effects. However, the weighted Ah-model does not provide a good absolute lifetime determination, but the percentage differences between simulations and test results are similar. It is therefore concluded that both models can be used to indicate which battery might last longer in a given category.

Obviously further work is required, and the tests currently under way will be useful to make further comparisons between simulation and lifetime tests. Additionally, it is important to note that lifetime prediction models for batteries so far were not checked against data of real battery tests. The results obtained here are therefore a major step forward for modeling the lifetime of a battery.

7. Recommendations

Making recommendations and benchmarking components by means of the method described so far first requires an easy assignment of a category to an RES. If the stress factors are known as a result of data evaluation using ITHESA, then the assignment is straightforward by means of a table and a least square fit for sets of stress factors that are outside the categories (Nieuwenhout 2004). However, this approach is only possible if very detailed data of RES's are available and cannot be used for many applications due to a lack of detailed data. As a result, a simplified method to establishing the appropriate category has been developed, which is based on general questions that try to identify the likely range of intensity levels of stress factors for the battery in the RES under investigation. These questions have been implemented by means of a Web-based software, Renewable Energy Smart Design Assistant Software (RESDAS), which is freely available at www.ecn.nl/resdas/.

Once the category is established, detailed recommendations are provided as regards the battery type, auxiliary equipment such as electrolyte circulation system, charge controller, and operating regime. Details of the recommendations for each individual category are given on the Web site of the Benchmarking project. (Nieuwenhout et al. 2005a). These recommendations extend to aspects of the operating conditions and settings for charge controllers. Table 9 provides a summary of the recommendations for batteries.

Table 9: Summary of Battery Recommendations for Different Categories

	Cat.1	Cat.2	Cat.3	Cat.4	Cat.5	Cat.6
Corrosion resistance (i.e. thick grids, special alloys, etc.)		Important feature	Very important feature	Important feature		
Acid circulation system or VRLA battery	Very important feature			Important feature		Important feature
Heavy-duty battery, resistance to AM shedding (i.e. tubular plate, pocket separators)	Important feature		Important feature	Very important feature		
Sulphation resistance (special charge method, auxiliary generator)	Important feature					Important feature

An obviously useful extension of this general approach is to use it in conjunction with simulation tools. To do this, however, it is necessary to obtain the current, voltage, and temperature of the battery with a time step of no more than 1 hour. None of the simulation tools that are presently used allows this. However, a test version of the Hybrid2 software (Baring-Gould 1996) has been created in which all required data are generated. The data can be used to create an SER, assign a category, and thus receive recommendations for the RES. More work is required to investigate and improve this further.

8. Outlook

RESDAS allows access to specific recommendations based on either detailed data of the RES or a general description of the RES. As yet, the output of ITHESA has to be entered manually so that RESDAS can be started. As only a few numerical values are required, this is not a real barrier of use.

For using RESDAS and ITHESA for planned systems, the barriers are much higher. First, only a test version of the Hybrid2 software provides the information necessary to create an SER so that the system can be evaluated and recommendations can be received. The output data of the test version of Hybrid2 can be processed in ITHESA, but this requires manual handling of data. It obviously would be interesting to have a closed process whereby the output of simulation tools could be processed directly by ITHESA. The Standard Evaluation Report generated by ITHESA would enable a detailed evaluation of how the components are likely to be used, and this would be a useful result.

An integrated planning tool requires a closed loop and iterations that lead to stable results. To achieve this, the economic assessment of components and component sizes made by some simulation tools must be taken into account. Only then will a stable outcome of the integrated planning tool exist.

Another extension of this project is the extension to other components of RES’s. For small wind turbines this has been done and shows that from wind data and energy output data of the wind turbine, stress factors and aging mechanisms/damage risks for wind turbines can be deduced. Although this process needs expert evaluation, it shows that the general approach of making specific recommendations based on data evaluation and categorization of systems can be extended (Peterschmidt 2004). It is possible that further data are required for an accurate categorization process of other components based on stress factors and aging mechanisms.

9. Conclusions

The analysis of RES data makes it possible to differentiate RES for different applications and in different locations into categories of similar use of the battery. In each category, the combination of stress factors is similar; therefore the aging risks will also be similar. Batteries suitable for a particular category will withstand these aging risks longer, and their performance values will remain acceptable longer. Test procedures have been identified that are relevant to the individual categories, and additional test procedures are suggested. Recommendations on a category-by-category basis are now possible to advise planners and users how to carry out a benchmarking process for selecting the most suitable battery. Manufacturers are provided with information concerning RES requirements so that they can develop batteries specifically for a certain category. All recommendations are accessible via the Internet, and help is given to identify the category into which a particular RES falls. The overall method can also be extended to other components.

The ultimate success of the method described in this paper will only be achieved once planners, manufacturers, operators, financial institutions, and researchers start to use the concepts which have been introduced and continue to refine the results further. Dissemination of the results therefore was and will continue to be an important aspect of the work reported here. Extension to other critical components, wind turbines, diesel generators and inverters, and further improvement of lifetime models are important. An ongoing comparison of battery data from test results and field data is required. This is an enormous task as verification of field data requires consistent data evaluation over the whole lifetime of the system and a determination of the performance values at the beginning of installation and the time of replacement.

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14. ABSTRACT *(Maximum 200 Words)*

This paper describes the results of the European Union (EU) Benchmarking Project, a 3-year, multi-agency research project to improve the design of renewable-based hybrid power systems based on the analysis of existing systems and the benchmarking of specific system components, most critically batteries. Based on the analysis of hundreds of power systems, efforts were made to classify different categories of similar use and then determine component-specific recommendations that will allow more consistent and longer product life. Based on the classification of different use types, assessments of critical ware factors could be conducted and recommendations of appropriate component selection undertaken. The project results make it possible to match most systems to a use category, thus allowing recommendations to improve project life.

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